Effect of Carbon Dioxide Enrichment on Radish Production Using Nutrient Film Technique (NFT)

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(NASA-TM-107198) EFFECT OF CARBON DIOXIDE ENRICHMENT ON RADISH PRODUCTION USING NUTRIENT FILM TECHNIQUE (NFT) (NASA) 17 p

N94-27411

Unclas

G3/51 0000297

Technical Memorandum 109198

March 1994

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Technical Memorandum 109198 March 1994

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ABSTRACT

Radish plants (*Raphanus sativus* L. cvs. Cherry Belle, Giant White Globe, and Early Scarlet Globe) were grown in four different CO_2 enriched environments, 0.04, 0.10, 0.50, and 1.00 kPa (400, 1000, 5000, 10000 ppm). Cultivar responses to CO_2 treatments varied, where cv. Cherry Belle showed no significant response to CO_2 enrichment, cv. Giant White Globe was moderately affected, and Early Scarlet Globe was strongly affected. Enrichment at 0.10 kPa led to greater root dry matter (DM) than 1.00 kPa for cv. Giant White Globe, whereas 0.10 kPa produced greater storage root, shoot, and root DM than 1.00 kPa for cv. Early Scarlet Globe. The data suggest that 1.00 kPa CO_2 may be detrimental to the growth of certain radish cultivars. Root:shoot ratios tended to increase with increasing CO_2 concentration. Water use efficiency (g biomass/kg H_2O) increased with increasing CO_2 enrichment, up to 0.5 kPa but then declined at the 1.00 kPa treatment. The total nitric acid used to maintain nutrient solution pH was lowest at the 1.00 kPa treatment as well, suggesting a decreased demand of nutrients by the plants at the highest CO_2 level.

LIST OF TABLES AND FIGURES

ACKNOWLEDGEMENTS

We would like to thank Elise Blaese and the Student Life Science Training Program (SLSTP) for screening several radish cultivars, from which three of the best yielding were selected for this study.

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INTRODUCTION

Interest has been generated by NASA in developing Controlled Ecological Life Support Systems (CELSS) for long-duration space missions and lunar habitations. On a smaller scale, salad crops have been given attention as a means to provide fresh food aboard Space Station Freedom and also to aid in the understanding of plant production in space. The project "Salad Machine" includes lettuce as one of the crops that will be considered for production on the Space Station. However, information pertaining to its culture in hydroponic systems is limited. Yield response surfaces for temperature, radiation (intensity and quality), and photoperiod have been investigated (Cracker et al., 1983; Inada et al., 1991), but CO_2 responses have not been thouroughly defined.

The atmosphere of human inhabited space craft tend to have CO_2 concentrations far above normal Earth ambient (0.035 kPa) levels. It is not unusual to report levels as great as 0.60 kPa in Space Shuttle and Mir quarters (D. Weigreffe, Bionetics Corp., 1993, personal communication; V. Polyakov, Cosmonaut, 1991, personal communication). Most CO_2 enrichment studies involving plants have focused on concentrations that are twice ambient levels. Carbon dioxide enrichment on radish production has shown that 0.06 - 0.07 kPa CO_2 resulted in improved yields over ambient concentrations (Sionit et al., 1982; Idso et al., 1988). However, effects of much higher CO_2 levels, that might occur in space habitats, have not been studied. It has been suggested that CO_2 enrichment much beyond 0.10 kPa (1000 ppm) may cause growth inhibition, resulting in yield reductions in some plants, e.g. cucumber (Peet, 1986). However, CO_2 levels at 0.50 kPa have revealed only minor effects in two soybean cultivars, with growth at 0.50 kPa being ~ 10% less than that at 0.10 kPa (Wheeler et al., 1993). Thus CO_2 effects may be species and cultivar dependent.

The objectives of this study were to 1) grow three cultivars of radish, with four levels of CO_2 enrichment, and 2) determine CO_2 effects on radish production and water use efficiencies (WUE) under moderate light conditions.

MATERIALS AND METHODS

A series of four 16-day radish (*Raphanus sativus* L.) studies was conducted in a 1.8 m x 2.4 m walk-in growth chamber (EGC Inc., Chagrin Falls, OH). Each study was set up as a

particular CO_2 treatment, and the CO_2 treatments were not repeated. Within each treatment cvs. Cherry Belle (CB), Giant White Globe (GWG), and Early Scarlet Globe (ESG) were grown at a density of 24 plants per square meter. Analysis of variance (ANOVA) was used to analyze

the cultivars individually. Mean separation was performed using Scheffe's test (SAS version 6.07, SAS Institute Inc. Cary, NC).

Environmental Conditions:

The four CO_2 treatments were 0.04, 0.10, 0.50, and 1.00 kPa (400, 1000, 5000, 10000 ppm). The 0.04 kPa treatment was chosen over normal ambient (0.035 kPa) to avoid periodic CO_2 increases resulting from human activity around the growth chamber. Levels of CO_2 in the chamber were monitored with an infrared gas analyzer (ANARAD Inc., Santa Barbara, CA) and controlled within 5% of setpoint with a dedicated computer system. Levels of CO_2 were 5% (coefficients of variation or CV) of the set point.

Irradiance in the chamber was provided with thirty 96-inch VHO Vita-Lite fluorescent lamps (Duro-Test Inc., North Bergen, NJ). Photosynthetic photon flux (PPF) levels for all tests averaged 230 μmol m^{-2} s^{-1} $\pm$ 3% CV using a 20 h light/4 h dark photoperiod. Temperatures for all tests averaged 23.9 $\pm$ 0.3 C light and 23.0 $\pm$ 0.4 C dark. Relative humidities were constant during the light/dark cycle and averaged 69 $\pm$ 1% .

Culture:

Plants were grown in eight trapezoidal-shaped, plastic culture trays (Mackowiak et al., 1989). Two kinds of plant support (tray) inserts were tested. The first insert was the same type used for soybean and wheat production studies (Mackowiak, et al., 1989) and consisted of rows of juxtapositioned black on white plastic in which was positioned a double piece of Nytex™ plastic fabric for wicking nutrient solution at the bottom of the tray to the seed. The second insert was similar but had holes containing the plastic strips rather than rows. This design had been used in lettuce production studies (Prince and Knott, 1989). Since insert style did not affect plant performance, it was not factored into the results and will not be discussed further.

The nutrient solution was composed of a modified half-strength Hoagland mix, and was monitored and replenished daily with a nutrient concentrate to maintain the solution electrical conductivity at 0.12 $\pm$ 0.02 S m^{-1} (Table 1). Elemental concentrations were monitored weekly using ICP spectroscopy. Nutrient solution pH was controlled automatically to 5.8 units with additions of 0.39 M nitric acid. Water was manually added to the reservoir each day to maintain a constant volume (80 L).

Twelve dry seeds were planted directly onto inserts for each trray. White acrylic germination covers were used to maintain high humidity around the seedlings for the first four days. At 7 days after planting (DAP), extra plants were removed, resulting in six plants per

tray. Both GWG and CB had three replicates (3 trays) and due to chamber space, ESG had two replicates.

Plants were harvested at 16 DAP, when leaf and storage root fresh mass (FM), and leaf area were recorded. Leaf, storage root, and fiberous root tissue were dried at 70 C for 48 h prior to measuring dry mass (DM).

RESULTS AND DISCUSSION

Biomass:

Results showed that CO_2 effects on yield were cultivar dependent for radish, just as had been reported for soybean (Wheeler et al., 1993). Cultivar CB showed no significant differences in growth parameters under the tested CO_2 levels (Table 2). Similar findings have been seen with cv. Sativas when testing CO_2 concentrations up to 1.0 kPa, but there were negative effects on growth at 3.0 kPa (Pfeufer and Krug, 1984).

There appeared to be a trend of greater leaf area at 0.10 kPa CO_2 enrichment for GWG and ESG (Fig 1a), although the differences were not significant (Table 2). Moderate enrichment has been shown to increase leaf area in many other crops; however, this was mainly associated with more extensive branching and less from individual leaf size (Lawlor and Mitchell, 1991).

There was some effect of CO_2 on root dry mass for both GWG and ESG, where CO_2 at 0.10 kPa produced significantly more root dry mass than at 1.00 kPa (Table 2). Soybean root biomass increased by 143% when CO_2 was raised from 0.035 to 0.67 kPa (Rogers et al., 1992). There also appeared to be a CO_2 effect with cv. ESG relative to storage root fresh mass and dry mass, where the 0.10 kPa treatment was significantly greater than the 1.00 kPa CO_2 treatment (Table 2). GWG and CB showed no significant differences for those variables. Enrichment to 0.07 kPa CO_2 has been reported to increase root:shoot ratios for radish, along with other root crops (Idso et al., 1988). We found similar results at 0.1 kPa CO_2; however, root:shoot ratios declined at the 1.00 kPa treatment (Fig 1b). The most productive treatments for storage root yields, namely, GWG at 0.50 kPa and ESG at 0.10 kPa CO_2, also had relatively high storage root standard errors. In fact, the coefficient of variation for GWG and ESG was about 38% greater than it was for CB, across CO_2 treatments. The greater variation may suggest that there was a higher degree of heterozygosity in ESG and GWG seed, which was accentuated by CO_2 enrichments.

Partitioning into the storage root per se, was not affected by CO_2 concentration; however, there were definite cultivar differences, where CB had consistently greater harvest index values than either GWG or ESG (Fig 1c). Although GWG had the lowest harvest index, it usually

had the largest storage roots and total biomass. Subsequently, it also had the greatest crop growth rate (g m^{-2} d^{-1}) and conversion efficiency per plant. Since CB had lower leaf area values, it may be a candidate for denser plantings. It also seems to be less affected by varying CO_2 concentrations (Table 2), leading to very predictable yields under the range of CO_2 and growing conditions used in these studies. It would not be surprising to learn that the variation in cultivar responses to CO_2 enrichment may also occur with other environmental parameters, so cultivar selection would depend on the the culture environment.

In a CELSS, great importance would be placed on efficient use of mass, volume, and energy. Sionit et al. (1982) have found that a combination of high PPF (1200 µmol m^{-2} s^{-1}) with CO_2 enrichment (0.07 kPa) improved radish yields, when using a 14 h light/10 h dark photoperiod. However, others have shown that the best light conversion efficiency for radish was with a 20 h light/04 h dark photoperiod combined with a thermoperiod that varied 5 C between light and dark cycles (Inada et al., 1991). In other words, plants that can produce highest yields in high PPF environments may not be the most energy (photon) efficient.

<u>Water and pH Control</u>:

Since all cultivars shared the same nutrient delivery system, water use (total evapotranspiration) represented all the cultivars combined, for any single CO_2 treatment. Water uptake was normalized to the following units: g total biomass/kg H_2O (i.e. water use efficiency or WUE). Increasing CO_2 above 0.04 kPa increased WUE, but WUE decreased at levels above 0.10 kPa CO_2 (Fig 2a). These results were similar to those reported for soybean (Wheeler et al., 1993); however, in this study, the relationship between total plant dry mass and WUE were highly correlated ($r^2 = 0.97$).

When NO_3^- is taken up by the plant, the release of HCO_3^- causes an increase in solution pH (Schon, 1992). Measurement of the nitric acid used for pH control in this study, resulted in an indirect method for determining NO_3^- uptake. Nitric acid use was normalized to the following units: g total biomass/mmole of acid (i.e. acid use efficiency or AUE). AUE was greatest at 0.10 kPa CO_2, which corresponded with the greatest total biomass (Fig 2b). Unlike WUE, AUE did not correlate well with total biomass ($r^2 = 0.55$), but it correlated well with leaf area ($r^2 = 0.82$). Nitrate has been found to accumulate in leaf vacuoles of leafy vegetables, such as lettuce, for subsequent use as a storage pool (Blom-Zandstra, 1989). Our results suggest that there may have been luxury consumption of nitrate, which was stored in leaf vacuoles, leading to lower AUEs in treatments having smaller leaf areas.

CONCLUSIONS

Effects of CO_2 on radish production in a hydroponic system were cultivar dependent, where CO_2 enrichment to 0.10 - 0.50 kPa improved yields and tended to increase leaf area for GWG and ESG. Carbon dioxide enrichment above 0.04 kPa had no effect on yields or on any of the other harvest parameters for CB. CB had a harvest index twice the value of GWG, but GWG produced up to 70% more storage root than CB, over all CO_2 treatments. Early Scarlet Globe ranked between the other two cultivars for a majority of harvest parameters. Total chamber WUE was similar to results found in previous CO_2 enrichment studies using soybean, where efficiency was greatest at moderately elevated CO_2 levels and was poorest at the lowest and highest CO_2 levels (i.e. 0.04 and 1.00 kPa). Acid Use Efficiency was greatest at 0.10 kPa CO_2 and lowest at 1.00 kPa, which may be related to inefficient use of nitrate at the highest CO_2 concentration. Based on yields, WUE, and AUE, it appears that CO_2 enrichment to 1.0 kPa was detrimental to GWG and ESG. The available literature suggests that other environmental parameters, i.e., photoperiod, irradiance, and thermoperiod, might also be adjusted, along with CO_2, for optimal radish production.

Table 1. Inorganic composition of the nutrient solution and replenishment solutions per liter.

SALT	NUTRIENT SOLUTION CONCENTRATION	REPLENISHMENT CONCENTRATION
	(mM)	(mM)
$Ca(NO_3)_2$	2.5	9.0
KNO_3	2.5	17.5
KH_2PO_4	0.5	5.0
$MgSO_4$	1.0	8.0
	(µM)	(µM)
Fe-EDTA	50.00	90.00
H_3BO_3	4.75	24.00
$MnCl_2$	3.70	18.50
$ZnSO_4$	0.52	3.20
$CuSO_4$	0.64	2.60
$(NH_4)_6Mo_7O_{24}$	0.02	0.05

Table 2. Effect of CO_2 concentration on the yield parameters of three radish cultivars.

Cultivar*	CO_2	SR**	SR	TOP	ROOT	LA**
	(kPa)	(g FM/plant)	(g DM/plant)	(g DM/plant)	(g DM/plant)	(cm)
CB	0.04	8.39 (0.53)	0.52 (0.04)	0.43 (0.04)	0.05 (0.01)	85 (7)
CB	0.10	8.51 (0.88)	0.56 (0.06)	0.47 (0.04)	0.05 (0.01)	84 (8)
CB	0.50	8.32 (0.50)	0.52 (0.03)	0.43 (0.04)	0.05 (0.01)	84 (6)
CB	1.00	8.20 (0.77)	0.51 (0.04)	0.44 (0.04)	0.03 (0.00)	76 (6)
Significance		*ns*	*ns*	*ns*	*ns*	*ns*
GWG	0.04	10.8 (1.37)	0.61 (0.07)	1.66 (0.15)	0.22 (0.02)	366 (33)
GWG	0.10	11.9 (1.40)	0.72 (0.08)	2.04 (0.12)	0.28 (0.03)	400 (24)
GWG	0.50	14.2 (2.02)	0.80 (0.10)	1.94 (0.14)	0.25 (0.03)	373 (21)
GWG	1.00	10.2 (1.64)	0.57 (0.09)	1.49 (0.11)	0.18 (0.02)	301 (20)
Significance		*ns*	*ns*	*ns*	$p < 0.05$	*ns*
ESG	0.04	9.5 (0.65)	0.59 (0.04)	0.76 (0.06)	0.09 (0.01)	160 (14)
ESG	0.10	12.7 (1.72)	0.87 (0.11)	1.12 (0.12)	0.12 (0.01)	195 (22)
ESG	0.50	11.5 (1.11)	0.77 (0.07)	0.84 (0.07)	0.07 (0.01)	174 (13)
ESG	1.00	7.5 (0.96)	0.47 (0.06)	0.67 (0.07)	0.05 (0.01)	144 (11)
Significance		$p < 0.05$	$p < 0.05$	$p < 0.05$	$p < 0.05$	*ns*

* CB = Cherry Belle, GWG = Giant White Globe, and ESG = Early Scarlet Globe.
** SR = storage root; LA = Leaf area. Standard errors are in parentheses.

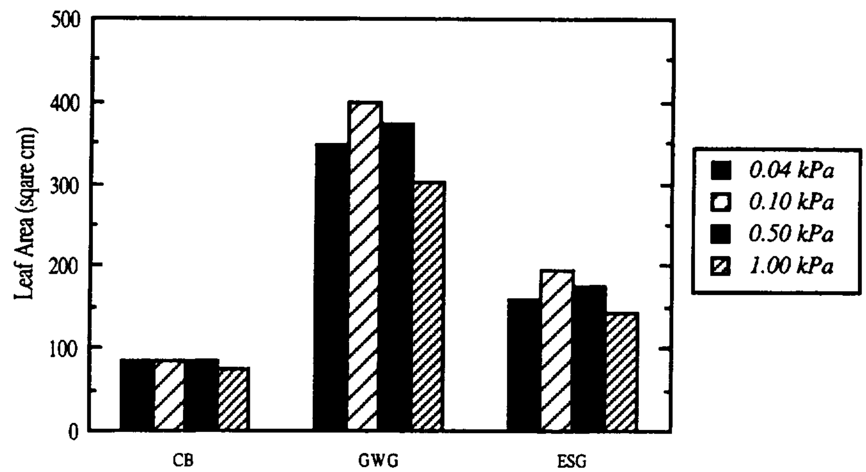

Fig 1a. Effect of CO_2 on radish leaf area. CB = Cherry Belle; GWG = Giant White Globe; ESG = Early Scarlet Globe.

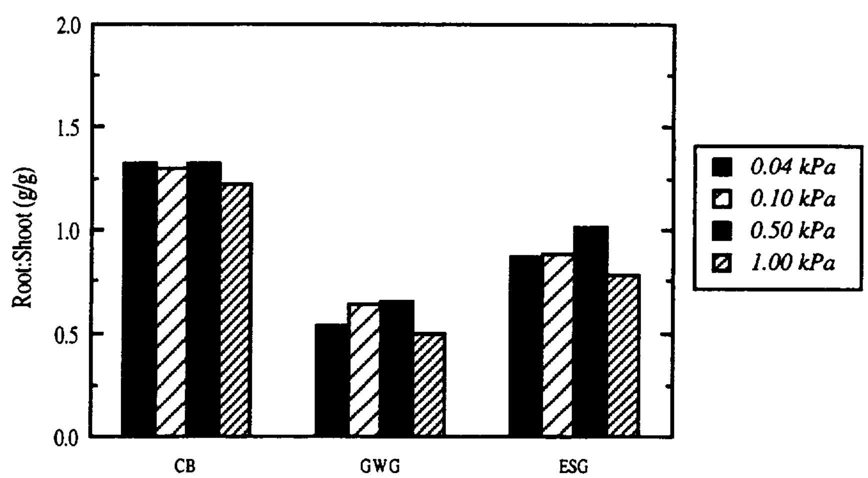

Fig 1b. Effect of CO_2 on radish root:shoot ratio. Cultivars same as in 1a.

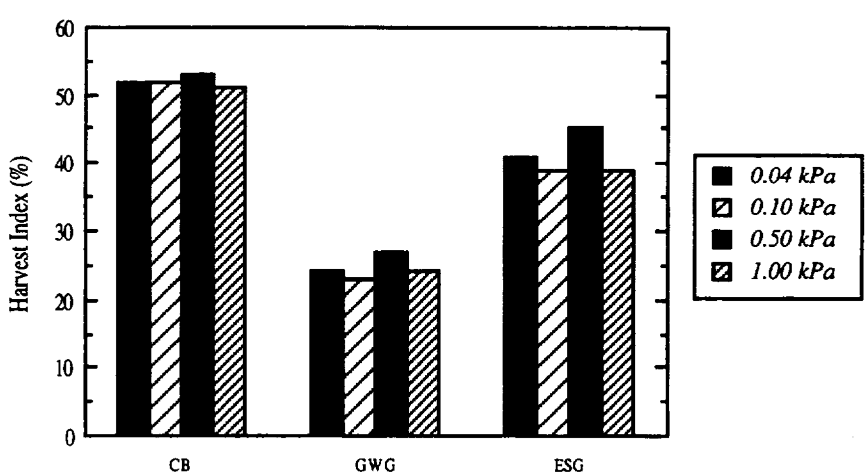

Fig 1c. Effect of CO_2 on radish harvest index. Cultivars same as in 1a.

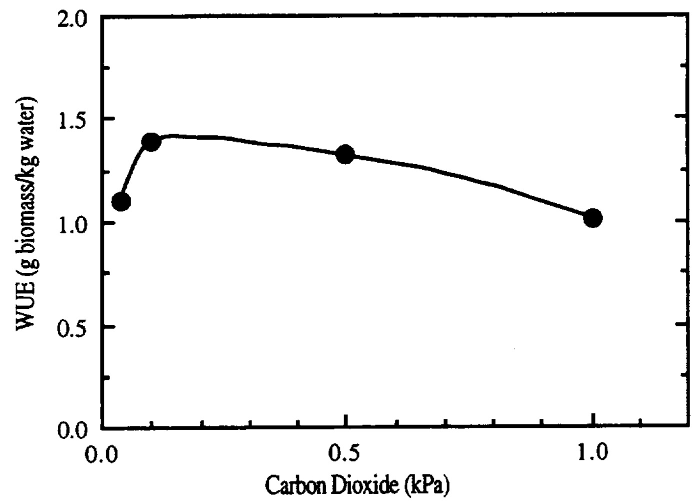

Fig. 2a. Effect of CO_2 on water use efficiencies (WUE). Since all cultivars shared the same nutrient tank, the values represent the combined evapotranspiration for all cultivars.

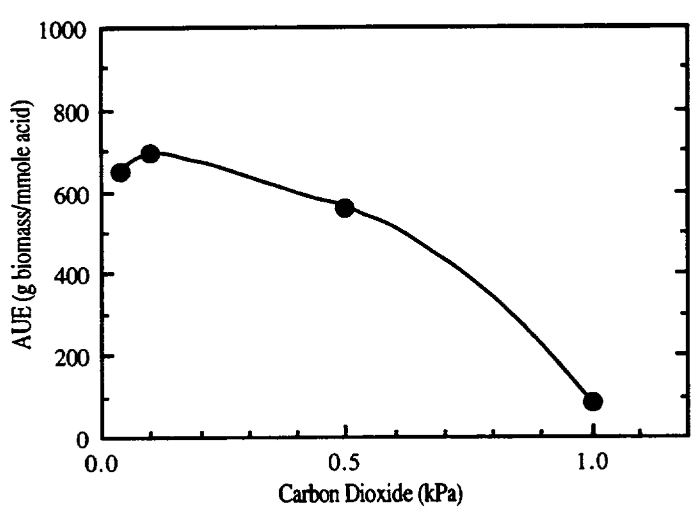

Fig. 2b. Effect of CO_2 on acid use efficiencies (AUE) from pH control. Since all cultivars shared the same nutrient tank, the values represent the combined use by all cultivars.

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	March 1994	Technical Memorandum

4. TITLE AND SUBTITLE
Effect of Carbon Dioxide Enrichment on Radish Production Using Nutrient Film Technique (NFT)

5. FUNDING NUMBERS

6. AUTHOR(S)
C.L. Mackowiak, L.M. Ruffe, N.C. Yorio and R.M. Wheeler

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
The Bionetics Corporation, Mail Code: BIO-3
(CLM, LMR, NCY) and NASA Biological Research and Life Support Office, Mail Code: MD-RES (RMW)
J.F. Kennedy Space Center, FL 32899

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Biomedical Operations and Research
Mail Code: MD
Kennedy Space Center, FL 32899

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
TM-109198

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified - Unlimited

12b. DISTRIBUTION CODE

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14. SUBJECT TERMS
radish, carbon dioxide, cultivar, supraoptimal, CELSS, water use efficiency

15. NUMBER OF PAGES 15

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	Unlimited

REV-435
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Author(s): C.L. Mackowiak, L.M. Ruffe, et al

Originating NASA Organization: Biomedical Operations and Research Office

Performing Organization (if different): The Bionetics Corporation

Contract/Grant/Interagency/Project Number(s): NAS10-11624

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